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Audibility of Spectral Switching in Head-Related Transfer Functions

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ABSTRACT

Binaural synthesis of a time-varying sound field is performed by updating head-related transfer functions (HRTFs). The updating is done to reflect the changes in the sound transmission to the listener's ears that occur as a result of moving sound. Unless the differences in HRTFs are sufficiently small, a direct switching between them will cause an audible artifact that is heard as a click. By modeling HRTFs as minimum-phase filters and pure delays, it is possible to study the effects of spectral and time switching separately. Time switching was studied in a previous investigation. This work presents preliminary results on minimum audible spectral switching (MASS).

1. INTRODUCTION

A head-related transfer function (HRTF) is defined as the ratio between the sound pressure at the ears of a listener and the sound pressure at the center of the head with the listener absent [1]. In this sense, HRTFs describe the directional dependent transformation that the sound pressure undergoes from the free field to the ears of the listener. As HRTFs convey the acoustic information needed to provide a listener with the correct directional cues it is possible to use them in order to synthesize three-dimensional sound. This technique is known as *binaural synthesis*.

Binaural synthesis is usually carried out by convolving an anechoic input signal with a set of HRTFs given in the time domain - denoted as head-related impulse responses (HRIR). The output from the convolution consists of two signals, one for each ear, which are usually delivered to a listener through equalized headphones. Now, in order to render three-dimensional sound for every possible direction, HRTFs should ideally be known for every possible direction. In practice, measurements of HRTFs [2, 3, 4] must be restricted to a limited spatial resolution. This aspect is of great importance when implementing systems that require synthesis

of moving sound. The reason is that moving sound, being a continuous phenomenon in space, has to be synthesized by switching between HRTFs which are simply not continuous in space.

1.1. Switching in HRTFs

When switching between HRTFs two aspects concerning their spatial resolution must be carefully examined in order to ensure that the sound transition is perceived smooth and continuous. First, the audibility of differences between the output of the switched HRTFs, and second, the audibility of artifacts created by the switching operation itself.

The first aspect relates to the human acuity for detecting small changes in the direction of a sound source. The smallest perceptible change is defined as the minimum audible angle (MAA), and it has been found to be about 1° for positions directly in front of listeners, increasing to more than 10° as sound sources move to the sides [5]. MAAs of 4° - 5° at 0° azimuth in the horizontal plane have been reported when using synthesized spatial audio on a headphone-based system [6]. It is important to note that the MAA only concerns to spatial resolution of static sound sources. Our ability to perceive sound source movement has been quantified by measuring the minimum audible movement angle (MAMA), which refers to the threshold angle for discriminating the direction of a moving sound. MAMAs are generally larger than MAAs. Both MAAs and MAMAs depend on direction and spectral content of the sound. MAMAs also depend on velocity of the movement [7]. For relatively slow moving sound in the front of a listener, MAMAs about 2° - 5° have been reported [8].

The second aspect concerning the audibility of the switching operation has received far less attention. Switching between HRTFs produces a sudden change in the filtered sound. This situation is depicted on Fig. 1 where a pure tone $x(t)$ is used as input signal and at time t_0 a HRTF switching from $(90^\circ, 0^\circ)$, which is directly to the left, to $(30^\circ, 0^\circ)$ is applied. Observe that the change is caused by differences in phase and amplitude before and after the switching. This sudden change can be perceived as an audible artifact, e.g. a click, which degrades

the quality of the synthesized sound. The audibility of these artifacts depends on several factors such as the spectral content of the input signal, the rate of the HRTF switching, and how large the differences between the characteristics of the HRTFs are.

HRTFs of nearby directions deviate only to a modest extent, and switching directly between them would be the same as switching directly between two signals that also deviate to a modest extent. This means that the closer the directions, the more alike the signals are. Therefore, it is hypothesized that for sufficiently small angular steps the signals are so alike that it is not possible to hear the artifacts. These angular steps must be smaller than the MAA, since if we switch more than the MAA, then the differences between HRTFs can be heard. In this sense it is desired to find the largest angle for which we can switch directly, thus, neither the differences nor switching artifacts can be heard.

Characteristics of the HRTFs can be separated into those related to time, i.e. inter-aural time differences (ITD), and those related to the spectral properties given by the minimum-phase transfer functions to the two ears. Studies have demonstrated that representing a HRTF by its

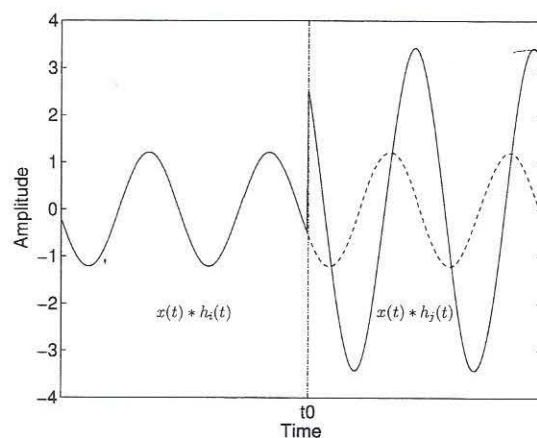


Fig. 1: Example of HRTF switching at time t_0 , where $x(t)$ is the input signal (pure tone), and h_i and h_j are the head-related impulse responses. The dashed line shows how the signal would have continued in case of no switching.

minimum-phase component along with the ITD results in signals that do not perceptually differ from those obtained with the original HRTF [9, 10]. This gives the option of separately manipulating the temporal and spectral characteristics of HRTFs, thus their individual contribution to the audibility of HRTFs switching can be evaluated. The temporal characteristic has been addressed in a previous study where the audibility of time switching was investigated by determining a minimum audible time switch (MATS) [11]. Results showed that the required spatial resolution for direct switching must be less than 1° for sound directly in front and about 2° - 3° for sound at the sides. The present study is focused on obtaining audibility thresholds of spectral switching, here denoted as minimum audible spectral switch (MASS).

2. EXPERIMENTAL METHOD

2.1. Subjects

Thirteen paid subjects participated in the listening experiment, nine males and four females. Their ages ranged from 22 to 31. Seven out of the thirteen subjects had participated in a previous experiment involving determination of MATSs. All subjects fulfilled the hearing requirements corresponding to hearing levels ≤ 10 dB HL at octave frequencies from 250 Hz to 4 kHz and ≤ 15 dB HL for 8 kHz.

2.2. Stimuli

Five seconds of broadband pink noise (20 Hz - 16 kHz) was used as source signal. The sampling frequency was 48 kHz. The pink noise was filtered with HRTFs measured with a high directional resolution on an artificial head [3]. Thirteen directions were selected in the upper hemisphere. These directions will be referred to as the nominal directions. Directions are given as (azimuth ϕ , elevation θ) in a polar coordinate system with horizontal axis and left-right poles. 90° and -90° azimuth correspond to left and right sides, 0° elevation to the frontal part of the horizontal plane, 180° elevation to the rear part of the horizontal plane, and 90° elevation to the upper part of the frontal plane. Five directions were selected in the median plane with a resolution of about 45° (0° azimuth, 0° , 44° , 90° , 136° and 180° elevation). Three directions were chosen on a

Direction (ϕ , θ)	ITD (μ s)	Approximated sample index
(0° , 0°)	2.3	0
(0° , 44°)	0.7	0
(0° , 90°)	0.7	0
(0° , 136°)	0.8	0
(0° , 180°)	2.8	0
(58° , 0°)	-439.7	21
(46° , 90°)	-433.4	21
(54° , 180°)	-430.9	21
(-56° , 0°)	430.8	21
(-46° , 90°)	435.3	21
(-54° , 180°)	430.6	21
(90° , 0°)	-621.5	30
(-90° , 0°)	624.6	30

Table 1: Nominal directions and ITD values of the HRTFs used in the listening experiment. Azimuth and elevation are given in polar coordinates where the poles are assigned to left and right. The approximated sample index corresponds to the number of zero-valued samples inserted at the beginning of the contralateral impulse response of the HRTFs to simulate the ITD.

cone of confusion to the left ((58° , 0°), (46° , 90°) and (54° , 180°)), and three on a similar cone to the right ((-56° , 0°), (-46° , 90°) and (-54° , 180°)). These directions were chosen to have the same ITD rather than being on the same geometrical cone, thus their azimuth varies with elevation. A small asymmetry of the head is reflected in a small difference between sides in the azimuth at 0° elevation. Directions directly to the sides, corresponding to (90° , 0°) and (-90° , 0°) were also selected. Nominal directions and corresponding ITDs are summarized in Table 1.

2.2.1. HRTF processing

The measured HRTFs were modeled as minimum-phase FIR filters with the ITD calculated separately and inserted to the contralateral impulse response. Minimum-phase filters were set to a length of 1.5 ms (72 taps at 48 kHz) since it was previously demonstrated that this length is sufficient to avoid audible effects of the truncation [12]. The DC value of each HRTF was set to unity gain (section 5.2

in [13]). ITD values were derived from the interaural differences in group delay of the excess-phase components of the HRTFs evaluated at 0 Hz [14]. The obtained values were rounded to the nearest sample.

2.2.2. Playback System

Stimuli were played back using a PC equipped with a professional audio card RME DIGI96/8 PST. The digital output of the audio card was connected to a D/A converter with 16 bit resolution at a sampling frequency of 48 kHz. From the D/A converter the signal went to a stereo amplifier (Pioneer A-616) modified to have a calibrated gain of 0 dB. A passive attenuator of -20 dB was then connected to the output of the amplifier in order to reduce its noise floor to inaudible levels. Finally, the stereo output signal from the attenuator was delivered to the listener through a pair of Beyerdynamic DT-990 circumaural headphones.

2.2.3. Headphone Equalization

Two minimum-phase filters were applied to the pink noise in order to compensate for the left and right headphone transfer functions respectively. The design of the equalization filters was based on headphone transfer functions (PTFs) measured on a blocked ear canal from 25 subjects. Five PTFs were obtained from each ear on each subject, and subjects were asked to reposition the headphones between measurements. PTFs were measured by using a maximum-length sequence (MLS) [15]. PTFs were averaged on sound power basis, and a minimum-phase representation of the inverse was computed for each ear. More details on the measurement and equalization techniques used can be found in [16].

By filtering the pink noise with the headphone equalization filters and adding fade-in and -out ramps of 10 ms, the sound stimulus was ready to be delivered to the headphones. Since the stimulus should be presented as a continuous sound, it was looped during playback and care was taken to avoid audible artifacts at the moment of looping. The gain of the system was calibrated so as the unfiltered pink noise simulated a free-field sound pressure level of 68 dB approximately.

2.3. Spectral switching

Spectral switching was implemented by updating the minimum-phase component of the HRTFs while keeping the ITD unchanged. The switching operation was set to work at a rate of 100 Hz. Switching was realized between two HRTFs that defined an arc centered on the nominal direction. In this sense, an increase in the switching angle meant that HRTFs for which the switching operation took place, moved in opposite directions equally far from the nominal direction.

For each nominal direction the HRTFs were switched in two ways, and thus two sets of filters were computed. One set corresponded to switching HRTFs along the azimuth angle, and the other set corresponded to switching HRTFs along the elevation angle. In the following parts of the article the two types of switching will be referred to as azimuth switching mode and elevation switching mode. As an example, when a sound was presented as coming directly from the front and the azimuth switching mode was used, the switching took place between HRTFs corresponding to directions in the horizontal plane. This particular scenario is depicted on Fig. 2. A HRTF switching between locations L1 and R1 was performed by periodically switching between $\text{HRTF}(\phi_1, 0^\circ)$ and $\text{HRTF}(-\phi_1, 0^\circ)$. Similarly, for a switching between locations L2 and R2 the switched HRTFs corresponded to $\text{HRTF}(\phi_2, 0^\circ)$ and $\text{HRTF}(-\phi_2, 0^\circ)$. If the elevation switching mode had been selected, HRTFs corresponding to directions in the median plane (up and down from the horizontal plane) would have been used instead. Note that for directions at $\pm 90^\circ$ azimuth the elevation switching mode cannot be applied. Therefore, two azimuth switching modes were implemented, one switching in the horizontal plane extending the angle horizontally ($0^\circ/180^\circ$ elevation) and the other switching in the frontal plane extending the angle vertically ($90^\circ/270^\circ$ elevation).

The maximum angular extent of the switching angle was set to $\pm 30^\circ$, which means a span of 60° . For the purpose of increasing the spatial resolution of the measured HRTFs a linear interpolation

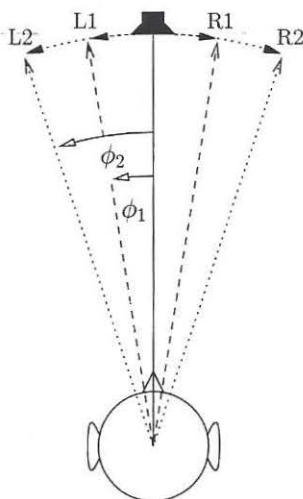


Fig. 2: Description of the switching strategy when a sound is presented as coming from the front (nominal direction), and the azimuth switching mode operates. A HRTF switching occurring for an angular extent of $\pm\phi_1$ creates periodic jumps from L1 to R1 and back to L1 every 10 ms (100 Hz switch rate). For an angular extent of $\pm\phi_2$ HRTFs corresponding to positions L2 and R2 are switched.

was applied to the time domain representations of the minimum-phase components. This operation was done off-line and in-between HRTFs with a resolution up to $\pm 0.25^\circ$ were calculated. Therefore, the smallest possible spectral switching had an associated angular separation of 0.5° . A total of 26 HRTFs' sets were constructed (13 nominal directions, each having two switching modes), and each set consisted of 121 pairs of minimum-phase filters.

2.4. Psychometric Method

The listening experiment was conducted by using the method of adjustment. This method offers the advantage of an active participation from the subject, thus, helping concentration and reducing boredom. The method is also relatively fast to carry out.

The response protocol used for the estimation of MASSs was identical to the one used in the

estimation of MATSs. A graphical interface that consisted of a slider and a push button labeled *OK* was displayed on a screen. The slider could be moved with the aid of a mouse along a vertical track-bar. The position of the slider along the track-bar controlled the angular separation between the HRTFs used for the spectral switching. The separation increased as the slider was moved towards the top and decreased as it moved towards the bottom.

During a single MASS determination, a combination of nominal direction/switching mode was presented to the subject. The task of the subject was to find the lowest position of the slider where he/she could just perceive the presence of a distortion in the signal. The distortion became easier to perceive as the angular extent of the switched HRTFs increased. Subjects were instructed to move the slider up and down several times before they gave a response. Subjects were also encouraged to perform the task as fast as they could. Once they had selected the slider position they entered a response by pressing the *OK* button. After a silence interval of 2 s a new stimulus was presented.

The scale of switching angles was contained within a frame equal to half the length of the track-bar. The range of switching angles went from 0.5° to 60° increasing linearly in steps of 0.5° . The position of the frame along the track-bar was randomized, and consequently, the position of the slider where spectral switching starts to operate. This was done to ensure that the threshold position varied along the track-bar. Below the lower end of the frame no switching was applied, and the switching angle above the upper end of the frame was equal to the maximum switching angle (60°). The initial position of the slider was randomly selected at either the top or the bottom of the track-bar. This ensured that the slider position was at a clear distance from threshold at the beginning of each presentation.

2.5. Experimental Design

The listening experiment consisted of two stages, one corresponding to familiarization and practice sessions and the other to the experiment where

data were collected. Subjects were located in a sound-insulated cabin with absorbing walls specially designed for subjective listening experiments. They were seated in front of a screen that displayed the graphical user interface described in 2.4. At the beginning of the experiment, the subjects were provided with written instructions about the task they were to accomplish. If necessary, subjects were given additional verbal explanation mainly in order to check their understanding and for practical matters. Right after that, subjects were firstly presented with a few stimuli in order to acquaint them with the task and the procedure. Posteriorly, they were presented with two or more blocks of stimuli for the practice sessions. All subjects had at least two practice blocks and inexperienced subjects completed two or three extra blocks prior to the main experiment.

One block consisted of thirteen stimuli. All nominal directions were presented in each block, and the switching modes, either seven times azimuth and six times elevation or conversely, were randomly assigned. Each combination of nominal direction and switching mode was repeated five times, giving a total of 130 responses per subject. Data were collected during two sessions that were held on different days. Each session consisted of 5 blocks and after each block a pause of 2 to 3 minutes was given to the subjects. Between the third and fourth block a longer pause was held.

3. RESULTS

Fig. 3 shows the raw data from all the thirteen subjects. The data are organized column-wise where each column represents responses from one subject. Data are grouped by nominal direction which are as well grouped by ITD. Top of Fig. 3 shows MASSs obtained for the azimuth switching mode. Bottom of Fig. 3 shows MASSs obtained for the elevation switching mode (for $\pm 90^\circ$ azimuth, vertical changes in azimuth). Responses marked with x are responses given in the part of the scale where no switching actually took place.

4. DISCUSSION

The number of responses given when no switching

took place corresponded to a 0.9% (15) of the total. These responses occurred for several nominal directions. Responses where the minimum value of the scale was selected as threshold corresponded to a 0.3% (5). The maximum of the scale was selected as threshold by 0.7% (11) of the total. Note that responses where the maximum of the scale was selected occurred exclusively for a nominal direction of (0° , 90°) and the elevation switching mode. Several subjects reported that it was more difficult to select a position of the slider when they were presented to this direction than to other directions. Furthermore, the spread of the responses for nominal directions in the median plane and elevation switching mode, tends to increase with elevation until a maximum around 90° elevation. For higher elevations (i.e. continuing down behind the listener) the spread decreases again. A similar tendency is also seen at the left and right cones, but here it seems more noticeable for the azimuth switching mode.

The larger spread of data for elevated directions can be explained by looking at how HRTFs change in this region. Fig. 4 illustrates this situation by showing changes in HRTFs as a function of the switching angle for two selected nominal directions. The top figures depict the changes for a sound direction at (0° , 90°) and the elevation switching mode. The bottom figures show changes for a sound direction at (54° , 180°) and the same switching mode. It can be observed that there actually are very small changes between HRTFs for the sound presented from above, when compared with the other direction especially in the region of high frequencies (7 - 16 kHz). This explains well that there are higher values of MASS and larger variations for directions above than for other directions.

The large intra-subject variation means that subjects may have given responses in a wide range, when presented to exactly the same condition, and it is important to understand why this occurs. Lets look in more detail on data from the particular subject who exhibited the largest variations between responses. Fig. 5 shows the responses, mean values and standard error of the means for this subject. Observe that for several conditions (nominal direction/switching mode), the range between responses

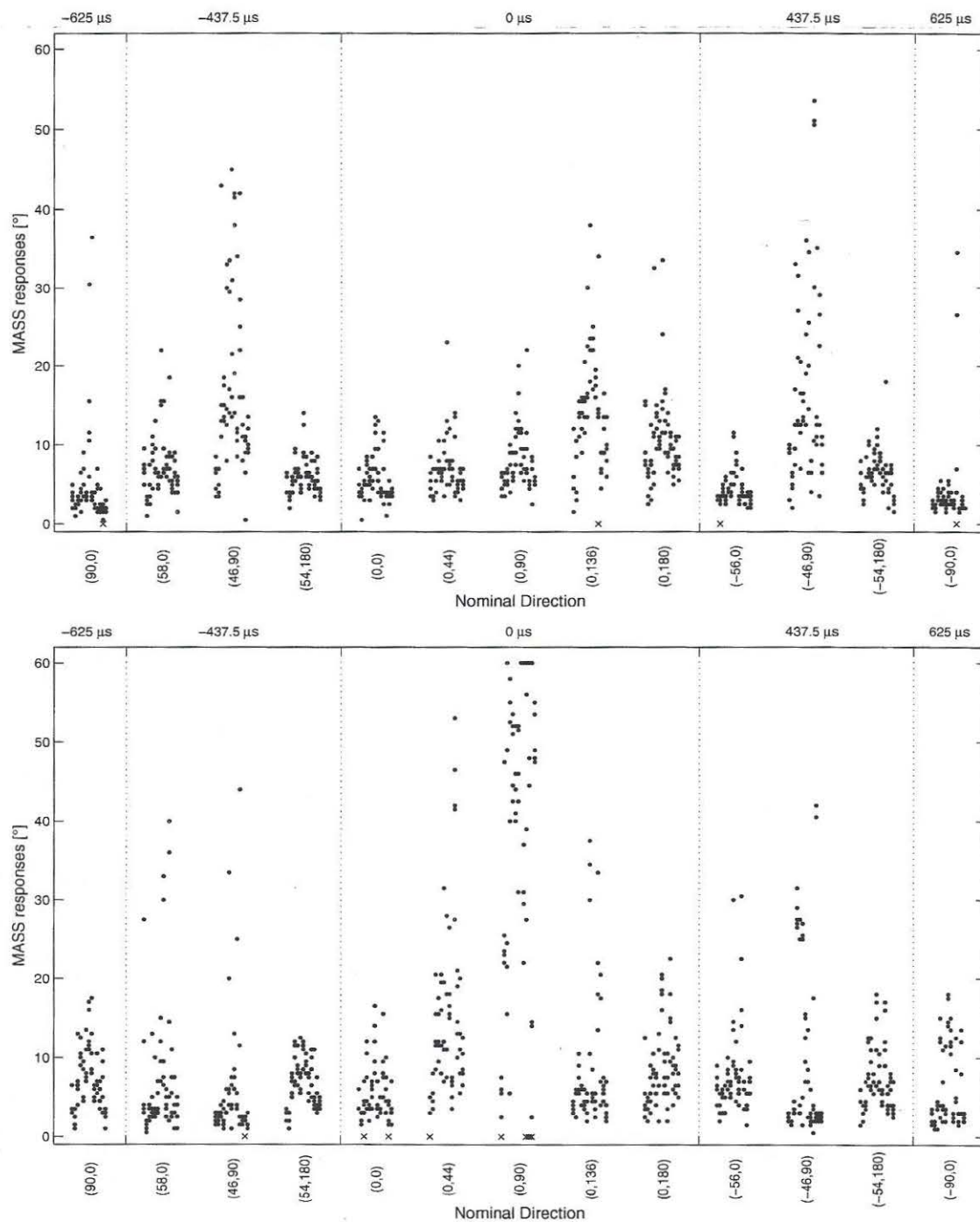


Fig. 3: Raw MASS data from all thirteen subjects. Data are grouped column-wise where each column corresponds to a subject. The top graph indicates MASSs for an azimuth switching mode. The bottom graph shows MASSs for an elevation switching mode.

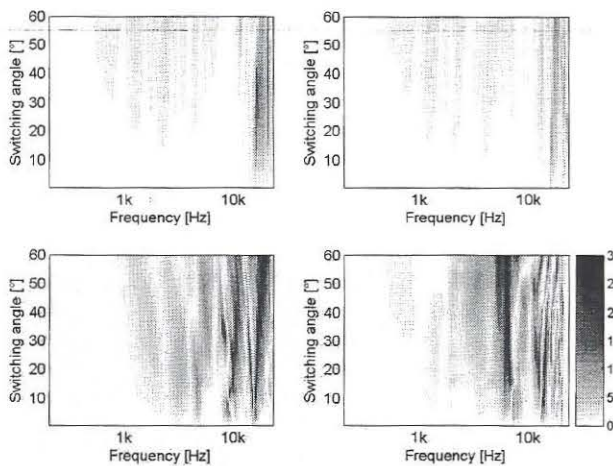


Fig. 4: Magnitude changes between HRTFs as a function of the switching angle for the elevation switching mode (left ear left column, right ear right column). Gray scale represents the magnitude of the differences in dB between HRTFs. Top figures depict magnitude differences that occur for a sound direction at $(0^\circ, 90^\circ)$. Bottom figures depict magnitude differences that occur for a sound direction at $(54^\circ, 180^\circ)$.

is quite large. Values up to 43° can be observed (data corresponding to the nominal direction $(-46^\circ, 90^\circ)$ for the azimuth switching mode). The particular case of the nominal direction corresponding to $(0^\circ, 90^\circ)$ and the elevation switching mode, shows that for one presentation the subject estimated a threshold where switching was not taking place, whereas for another presentation the subject estimated a threshold at the highest possible value that could be selected.

The high degree of variance may be a consequence of the resolution used for the switching operation. Actually, another subject reported that sometimes he put the slider on a fixed position (around threshold) where he did not perceive distortion and after a while (it is assumed a hundreds of milliseconds) he started to hear a distortion. Conversely, he also reported that sometimes he located the slider on a position where he still heard a distortion and then the distortion tended to disappear, even when he did not move the slider

again. At this point it is important to note that a threshold is not a fixed value, but the transition from inaudible to audible takes place over a range. If this range occupies much of the slider scale, the method of adjustment is not suitable. A movement of the slider should be accompanied by a clearly audible change. These observations constitute additional evidence suggesting that the angular resolution for the switching might have been excessively high for the purpose of the experiment. In the context of these observations the authors decided not to give any conclusive remarks.

A coarser angular resolution between HRTFs might be needed in order to obtain more reliable and consistent responses. It is also noticed that since the variation is not the same for

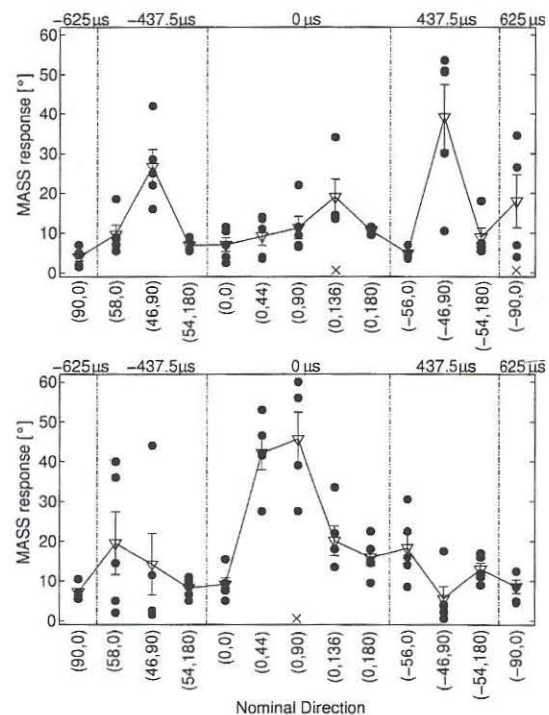


Fig. 5: Individual responses from the subject who showed the largest variation. Top figure shows data obtained for an azimuth switching mode. Bottom figure shows data obtained for an elevation switching mode. Triangles indicate mean and error bars indicate standard error of the mean (s.e.m.).

the different directions the angular resolution used should change depending on the direction presented.

A re-design of the experiment in order to apply the necessary changes described in this section is currently in progress.

5. ACKNOWLEDGMENTS

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